

Design of a Dynamic Rollover Test System

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ABSTRACT

A dynamic rollover test system (DRoTS) capable of simulating rollover crashes in a laboratory was designed for research use at the University of Virginia. The goal of the current study is to describe the system's capabilities and specifications as well as to explore the limitations of the system's ability to simulate rollover crashes. The test apparatus was designed to permit simulation of a single roof-to-ground interaction of a rollover crash with the potential to be modified for evaluation of pre-roof contact occupant motion. Special considerations were made to permit testing of both dummies and post-mortem human surrogates in both production vehicles and a parametric test buck. DRoTS permits vertical translation, pitch, and roll of the test vehicle while constraining longitudinal and lateral translations and yaw. The study details the ranges of test parameters capable with the DRoTS and evaluates the limitations of the system relative to rollover crash conditions. Considerations on the use of the test system and the constraints applied to the vehicle are evaluated through analytical analysis and computational modeling. The results of the analyses suggest that the DRoTS design is capable of testing vehicles in a wide variety of conditions while maintaining reasonable fidelity to rollover crashes during the duration of a single vehicle roof-to-ground interaction.

INTRODUCTION

Rollover crashes are responsible for more than one-third of all road traffic occupant fatalities while only accounting for 3% of crashes (NHTSA, 2009a). While at least some of the fatalities attributed to rollover crashes result from other crash modes (frontal, side, etc.) that precede or follow rollovers, rollover crashes still constitute a significant public health problem. In

an effort to address this problem, researchers have been simulating rollovers using a variety of test methods for more than 40 years (c.f. Chou et al. 2005). Several methods have been developed to provoke vehicle rollover by inducing a trip or generating trip kinematics including the widely-used (angled) dolly rollover test included in FMVSS No. 208 (Orlowski et al. 1985, Bahling et al. 1990, SAE 1999, etc.), ramp/corkscrew testing (SAE 1980, Berg et al. 2002), steer-induced rollover testing (Ennos 1971, Wilson and Gannon 1972, Larson et al. 2000), controlled soil trip tests (Thomas et al. 1989, Cooperrider et al. 1990, Cooperrider et al. 1998), embankment tests (Wilson and Gannon 1972), curb trip tests (Thomas et al. 1989, Cooperrider et al. 1990), barrier rollover tests (Habberstad and Thomas 1986), and deceleration rollover sled or flat dolly tests (Rossey 2001, Hughes et al. 2002, Balavich and Nayef 2002, Kerrigan et al. 2010). A concern associated with these types of tests has been an apparent lack of repeatability in either the boundary conditions applied to the vehicle at rollover initiation (trip or roof-to-ground contact) or in the response of the vehicle and/or its occupants during the test. Even in tests designed specifically to demonstrate repeatability (Kerrigan et al. 2010), rollover tests have been shown to have high sensitivity to initial conditions, boundary conditions, and vehicle inertial properties.

Two rollover test systems have been developed to provide for precise specification of the vehicle's kinematic parameters at the instant of roof to ground contact: the Controlled Rollover Impact System (CRIS) and the Jordan Rollover System (JRS) (Figure 1). The CRIS system (Cooper et al. 2001, Moffat et al. 2003) is mounted on a moving flatbed semi-trailer that supports a vehicle above the ground with adjustable height support pins. The vehicle is (rotationally) accelerated to the desired roll rate

while the semi-trailer accelerates to the desired translational velocity, and then vehicle is released, at which point the vehicle strikes the ground and rolls to rest while totally unconstrained. The test vehicle interfaces with the drive systems via a 469 kg fixture that is welded/fastened to the vehicle frame (Moffat et al. 2003). Since it can take several revolutions to accelerate the vehicle up to the desired roll rate with the CRIS roll drive system, ATD occupants are restrained in their pre-impact orientations with a supplemental system that releases the occupants just prior to initial contact. The first roof impact is controlled by prescribing the roll rate, translational and vertical velocity and vehicle roll, yaw, and pitch. The translational velocity is controlled by the speed of the semi-trailer while vertical velocity is determined from the drop height. The CRIS allows pitch and yaw angles to be set from negative 15 to positive 15 degrees. The accuracy of the roll angle at impact has been reported to be ± 4 degrees, and the CRIS has been tested up to a 360 deg/s roll rate with an accuracy of ± 2 deg/s. Due to the way the CRIS controls for the accuracy of the test parameters at contact, the vehicle is released in a target area, rather than a precise location. Thus, a relatively large outdoor space is necessary for the testing. Despite this, the CRIS system has been shown to produce repeatable vehicle kinematic parameters at the initiation of roof-to-ground contact, and it allows for completely unconstrained roll kinematics after test initiation.



Figure 1. The CRIS test system (top) and the JRS test system (bottom). Source: Cooper et al. 2001, and Friedman and Hutchison 2008.

In the JRS (Jordan and Bish 2005, Friedman and Jordan 2008, etc.) the test vehicle is held in a supporting fixture, rotated from rest to an inverted state, and then dropped onto a moving road surface. After a single roll along the road surface the vehicle's vertical translation is arrested (using brakes) and the vehicle is allowed to rotate to rest while suspended to prevent any additional ground contacts. The roll drive coupled to the supporting fixture rotates the vehicle about the roll axis at a desired roll rate and the fixture controls the pitch, roll, and yaw angles at impact (Friedman and Hutchison 2008). The lateral and vertical velocities are controlled by the speed of the road bed and the drop height, respectively, and the roadbed drive system is coupled to the roll drive system. This coupling ensures that the relationship between the road bed speed and the roll rate are fixed by the diameter of the roll drive sheave. Current use of the JRS has reported a maximum rate of rotation at 360 deg/s (Friedman et al. 2003). Similarly, the system has been specified to allow yaw angles up to plus or minus 30 degrees and a pitch angle from 0 to 10 degrees (Hutchison and Friedman 2008). While some of the test parameters can be specified exactly through mechanical system controls, the speed of the road bed, and thus the roll rate imposed by the drive system, are controlled by a pneumatic system that has some variability. Repeatability in testing has been reported in the literature, but test data were not reported in great detail and there was some variation reported in test parameters for the repeated tests (Bish et al. 2008). While the JRS allows for rollover tests to be performed in a small space inside a laboratory, coupling of the roll and translational drives makes independent specification of the road velocity and angular velocity difficult. Additionally, the short road surface (2.7 m) limits the ranges of test parameters and requires special consideration to prevent vehicle contact with the roadbed edge. Furthermore, the JRS only permits a single roll without allowing subsequent rolls, which can be either a benefit or a disadvantage depending on the goals of a particular test. Lastly, the JRS constrains the vehicle's motion during the roll sequence, which could affect how well the test is able to simulate rollover crash conditions. These constraints have been previously investigated (Friedman and Hutchison 2008), however more analysis is needed to adequately characterize the effects of the constraints.

In the final rule updating FMVSS No. 216 (NHTSA 2009b), the National Highway Traffic Safety Administration (NHTSA) addressed comments submitted regarding the use of the CRIS and JRS in dynamic rollover crash testing. Comments regarding the CRIS were chiefly related to the lack of demonstrated repeatability of the CRIS system after initial roof-to-ground contact. The NHTSA stated that while dummy injury risk metrics have demonstrated repeatability during the

first roof-to-ground contact, the “relevance of the dummy measurements for rollover impacts has not been established” and that a long-term research program would be necessary to identify real world correlation of the test procedure. The NHTSA’s responses regarding the JRS were similar with regard to the need to establish the system’s repeatability and to demonstrate the biofidelity of a dummy (and to determine appropriate injury criteria prior to its use). Additionally NHTSA explained that it had “remaining questions regarding the setup, conduct, and evaluation of the JRS test procedure”. Specifically, NHTSA questioned the methods used to determine test parameters (drop height, roll rate and road surface speed) used in JRS tests, the lack of established vehicle performance criteria and instrumentation and the lack of ability to simulate lateral accelerations to vehicle occupants prior to roof-to-ground contact, all of which presumably apply to both the CRIS and the JRS.

In an effort to shed some light on the questions raised regarding dynamic rollover testing, the University of Virginia Center for Applied Biomechanics and the NHTSA recently began a long-term research collaboration aimed to, among other tasks, design, construct, and perform tests with a dynamic rollover crash test fixture developed specifically for research. Specifically, the test fixture will be used to (1) perform parametric sensitivity analyses to determine how occupant injury risk is affected by changes in vehicle, crash, and occupant parameters, (2) evaluate external and internal biofidelity of existing anthropomorphic test devices (ATDs) relative to post mortem human surrogates, and (3) examine the extent to which a dynamic rollover test can be used to evaluate vehicle crashworthiness via dummy injury risk assessment for restrained occupants. Many of the previously used test methods have been widely criticized for lacking repeatability, fidelity (or similarity of conditions) to real rollover crashes in terms of the test parameters or vehicle kinematics, and for utilizing crash dummies without well defined injury criteria and injury assessment reference values. As a result, the research program is aimed at detailed investigation and presentation of repeatability, identification of vehicle-specific test parameters that retain fidelity to rollover crashes, injury criteria identification and ATD biofidelity assessments.

This study presents the results of a collaborative effort aimed at the design and development of a test fixture intended to support and address the goals of the research effort. This study is broken up into two major parts. The first is a detailed description of the dynamic rollover test system (DRoTS) including descriptions of the expected performance of the two

major drive systems. Since the DRoTS applies constraints to the vehicle to permit controlled repeatable rollover crash tests inside a laboratory, a number of kinematic and kinetic differences between rollover crashes and DRoTS tests designed to simulate rollover crashes have been identified. The second part of this study describes these differences in detail and evaluates what these differences mean in terms of interpreting the results of DRoTS tests and their applicability in simulating rollover crashes.

SYSTEM DESCRIPTION

The DRoTS is designed to simulate the portion of a rollover crash from the first instant that a part of the vehicle’s body (door, quarter panel, roof, roof rail, etc.) contacts the ground until the vehicle rotates enough that the roof is no longer in contact with the ground. In this study, this period is often referred to as a single “roof-to-ground” interaction of a rollover event, however this could also include interaction between the vehicle pillars or even door/side panels and the ground. The DRoTS permits rollover crash tests inside a laboratory by simulating the translational velocity differential between the moving vehicle and stationary ground in a rollover crash using a translating road surface and a vehicle that is not permitted to translate (Figure 2). In a DRoTS test, the vehicle is accelerated to the test (angular) velocity while rotating from 0 degrees to the test rotation angle, the road surface is accelerated to the test (linear) velocity, the vehicle is dropped onto the moving road surface (“roadbed”), the vehicle is permitted to roll across the road surface, and at the end of the test two separate brake systems are actuated to eliminate vertical (translational) and roll (rotational) motion of the vehicle.

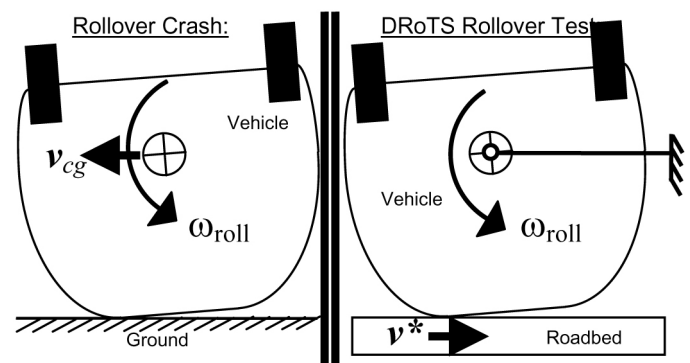


Figure 2. The lateral motion of the vehicle CG in a rollover crash is simulated with lateral motion of the simulated ground in a DRoTS rollover test.

COORDINATE SYSTEMS AND CONSTRAINTS

To describe the constraints applied to the vehicle, it is convenient to define two different coordinate systems: one global or inertial system, and one local vehicle-fixed system (Figure 3). The local vehicle system is defined using the SAE J211 convention with the X' -axis aligned with the longitudinal axis of the vehicle and positive directed toward the front of the vehicle, the Y' -axis aligned with the lateral axis of the vehicle with positive pointing toward the right hand side of the vehicle, and with the Z' -axis aligned with the vertical axis of the vehicle with positive pointing down. The global or inertial reference frame axes are defined to be coincident with those of the vehicle-fixed frame when the vehicle is resting on its wheels and oriented with a 90 degree yaw relative to the direction of the road bed motion.

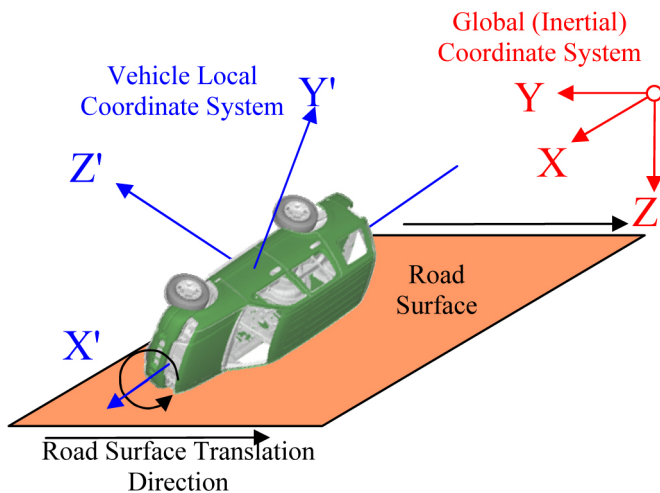


Figure 3. Local and global coordinate system definitions.

During the roof-to-ground interaction period of a test, the DRoTS permits the vehicle to rotate freely about the local X' -axis (the roll axis) and the global Y -axis (simulating vehicle pitch), but rotations about the global Z -axis are constrained. The vehicle CG is free to translate in the global Z direction, but CG translations in the X and Y directions are constrained. Translations of the vehicle in the Y -direction are simulated with the moving road surface and translations in the X -direction are constrained to prevent damage to the fixture (more discussion of this is included in *Analysis of Constraints*). It is important to note that while CG motions in the X direction are

constrained, this constraint has no effect on rotations about the global Y -axis. Additionally, testing in a 90 degree yaw configuration, the roll axis (X') is constrained to remain in the global XZ plane for the duration of the test, but when testing with less than 90 degrees of yaw, the roll axis (X') remains in a plane perpendicular to the road surface but rotated about the global Z -axis by an amount equal to 90 degrees minus the yaw angle.

PARAMETERS AND CAPABILITIES

The system is designed to perform tests using vehicles ranging in geometric (size) and inertial properties (mass/moment of inertia) from that of a 2010 Mini Cooper to a 2010 Ford F-250. The system should be capable of testing vehicles that have strength to weight ratios higher than any vehicles currently available (as high as 6.0 for a vehicle as heavy as a Ford F-250). The system has been designed to test vehicles with a set of six test parameters that can be independently adjusted over the ranges of the system's capability. The ranges were determined mostly by physical limitations of the test space:

- **Vertical Drop Distance:** The system is capable of drop distances between 0 and 0.305 m with the largest vehicle (F-250) and larger heights can be achieved with smaller vehicles. Drop height is achieved by releasing the vehicle from its vertical support at a height such that its center of gravity (CG) will translate downward the specified drop height (while rotating to the specified roll angle) before any part of the vehicle contacts the road surface.
- **Roadbed Velocity:** Velocities between 3.8-17.0 m/s (with the full roadbed) can be obtained by varying the pressure in the sled system and higher velocities can also be achieved by adjusting the mass of the roadbed by sectioning or adding ballast. See *Roadbed* in *Test Fixture Components* or more information.
- **Pitch Angle at Contact:** Angles from 0 to 15 degrees can be achieved with the largest vehicle (F-250) and the largest drop height (0.305 m), but larger angles can be achieved with smaller vehicles and lower drop heights.
- **Constant (Fixed) Yaw Angle:** Vehicles can be tested in barrel roll configurations at 90 degrees yaw, or with yaw angles as low as 60 degrees. Variation in yaw angle is achieved by rotating the gantry structure relative to the roadbed sled guidance system.
- **Roll Angle at Contact:** The rotational drive system is capable of rotating the vehicle up to angles as high as

180 degrees. However greater roll angles at contact can be achieved by allowing the vehicle to rotate freely (not under any acceleration) prior to contacting the roadbed. See *Rotational Drive in Test Fixture Components* and *Rotational Driver Performance* for more information.

- **Roll Velocity at Contact:** The rotational drive's performance is a function of vehicle moment of inertia and roll angle at contact. For a 90 degree roll angle a 1998 Ford Expedition ($I = 1410 \text{ kg m}^2$) can be tested as high as 260 deg/s, and for a 180 deg of roll angle a 1998 Chevy Metro ($I = 274 \text{ kg m}^2$) can be tested at rotational rates as low as 60 deg/s. See *Rotational Drive in Test Fixture Components* for more information.

Any combination of these parameters can be obtained for any tests provided that the parameters are within the ranges specified above.

TEST FIXTURE COMPONENTS

The DRoTS test fixture consists of a series of individual components or systems that together function as a rollover test fixture (Figure 4 and Figure 5). The following provides a basic description of the construction and function of each of the components. With the largest vehicle (Ford F-250) mounted in the test fixture and configured for a 15 degree pitch, 155 degree roll angle, 90 degree yaw angle test with a 0.305 m drop height, the entire test fixture occupies a space approximately 4.92 m high, 8.98 m long, and 7.75 m wide. For the same configuration with a 60 degree yaw angle, the structure's height remains the same, the length is reduced to approximately 6.68 m, and the width is increased to approximately 9.76 m.

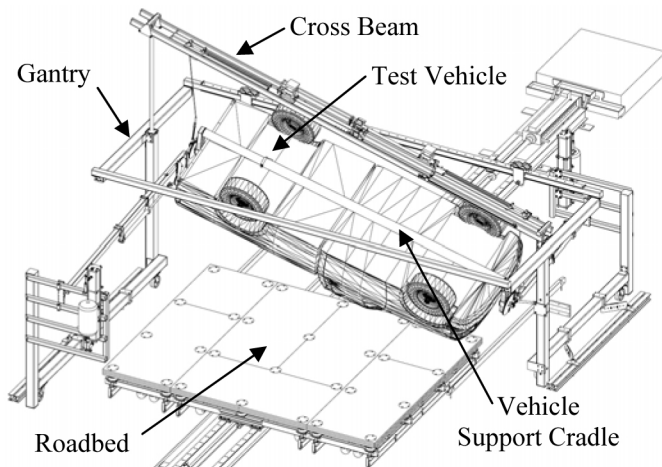


Figure 4. Isometric view of the DRoTS design with a Ford F-250 loaded with a 15 degree pitch, and 155 degree roll angle (90 degree yaw).

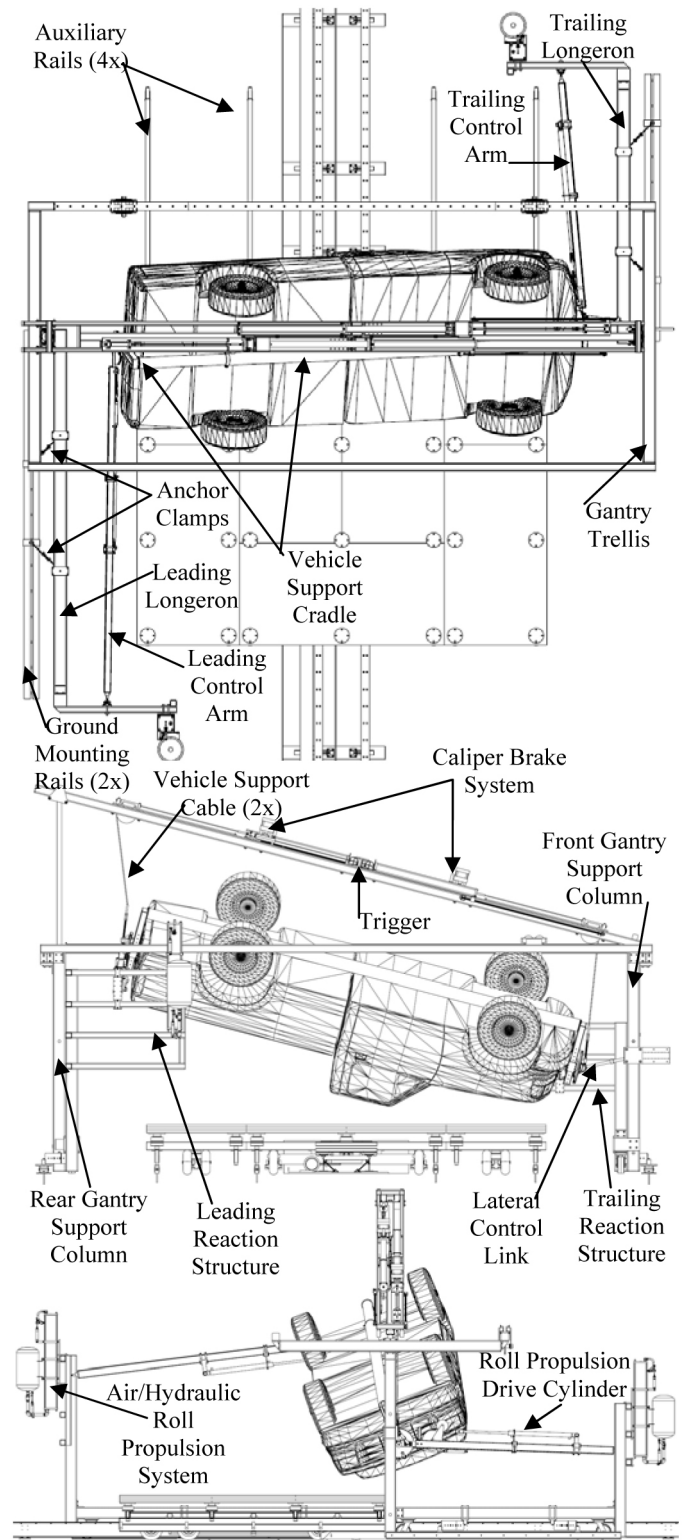


Figure 5. Top, front and right side views of the DRoTS design with a Ford F-250 loaded with a 15 degree pitch, and 155 deg roll angle (90 degree yaw).

“Roadbed” Road Surface Sled

The roadbed is the structure used to simulate the road surface in DRoTS tests. It is supported, propelled, guided, and decelerated by the deceleration sled system. The top surface of the roadbed is 4.88 m wide and 3.66 m long (Figure 6) to which any coating can be applied to achieve the desired friction level. The top surface is composed of a series of pieces of plywood (101.6 mm thick) bound together by a specialized adhesive technique designed to maximize the stiffness of the structure. The wood structure is supported by a series of 24 load cells connected to a base structure constructed of steel tubing. The load cells are oriented such that both normal and shear (both directions) forces applied to the top surface of the roadbed can be measured with the load cells. The top surface of the sled is instrumented with accelerometers to measure any accelerations of the mass above the load cells for inertial compensation of the measured load. The roadbed sled is configured in a way that permits detachment of one or both 1.22 m × 3.66 m side sections to permit use of the road bed with the center section alone, with the center section and either side section, or with both side sections. The roadbed sled weighs approximately 1360 kg, with the weight distributed evenly (each side section weighs approximately 340 kg). The roadbed center section is equipped with a ballast chamber permitting the addition of a maximum of 900 kg of ballast weight. The roadbed is equipped with an air suspension system that allows it to float over the main guidance rails of the deceleration sled system with its weight supported by a series of wheels that roll directly on the floor of the test facility. During interaction with the vehicle, normal forces applied to top of the roadbed will cause the air suspension system to deflect and the forces are transferred to the test facility floor through the sled guidance rails and an additional set of auxiliary rails, running parallel to them in the area where the vehicle interacts with the roadbed.

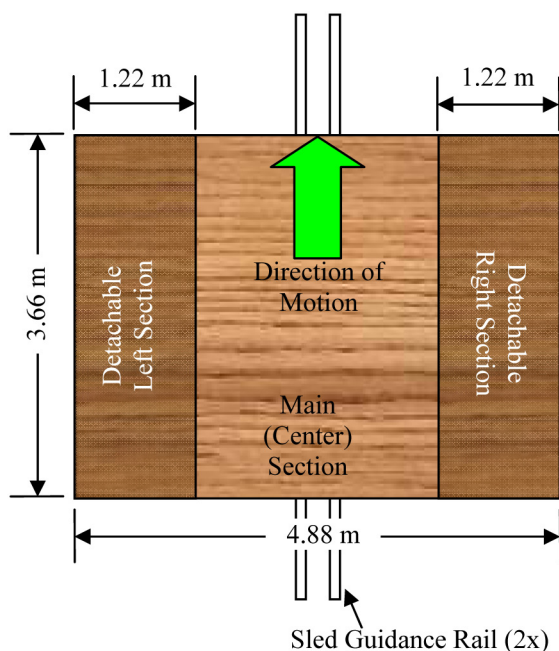


Figure 6. Road bed sled schematic.

Deceleration Sled System

The test fixture will utilize the H.I.T.S. 714 (VIA Systems, Salinas, CA) deceleration sled system installed at the University of Virginia Center for Applied Biomechanics to propel, guide and decelerate the roadbed sled. The sled's pneumatic propulsion system consists of a 146 mm diameter cylinder that runs the length of the 23.7 m guidance rails, and is fed by air from a pair of 454 liter ASME storage tanks. The cylinder's piston is attached to a steel cable, that runs around a sheave near the impact end of the guidance rails, and back up to the launch end, where it is connected to the roadbed. During a test, pressurized air from the tanks is allowed to pass into the drive cylinder, and the cylinder's piston begins to accelerate toward the sled's launch end, which pulls the cable around the sheave and accelerates the roadbed toward the impact end. Once the roadbed reaches the impact end, it is decelerated by a programmable hydraulic decelerator with a 1.17 m stroke. The guidance rails consist of a pair of 203 mm I-beams with 6.4 mm thick pieces of cold rolled steel plate attached to the top surfaces. To permit use of the 4.88 m wide roadbed sled, a set of four auxiliary rails (3.66 m long) will be installed to support the road surface in the impact area.

The pneumatic sled system is capable of being utilized at staging pressures between 100 and 1310 kPa. Using a 13.7 m run up distance and estimates for piston friction and guidance rail friction empirically derived from numerous sled runs, achievable road speed envelopes were determined (adiabatic gas expansion assumption) as a function of roadbed mass (Figure 7). When the center section only is used, test speeds between 5.8 and 24 m/s can be achieved. But when the full roadbed with full ballast is used, test speed performance ranges from 2.5 to 13.1 m/s.

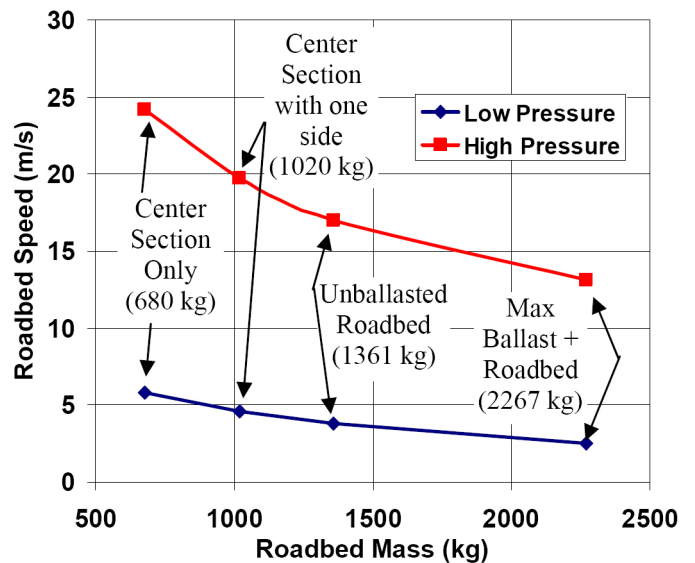


Figure 7. Predicted performance of the translational drive as a function of the road bed mass for three different roadbed configurations and the maximum ballast configuration. Any pressure between the low and high pressure indicated can be used to achieve the desired road speed.

Gantry

The Gantry consists of two sides, connected together by a rectangular trellis structure, which spans the sled and auxiliary rails, that provides torsional stability to the structure as well as assistance in loading vehicles into the gantry. Each side consists of a main (front or rear) support column connected to a longeron (leading or trailing) with a reaction structure (leading or trailing) attached to the end of the longeron. Each of the support columns includes an internally mounted hydraulic cylinder that is used to raise, lower, and adjust the angle of the cross beam (and thus the test vehicle) for pre-test positioning. The fixture is designed such that one side is capable of a larger vertical displacement than the other (one hydraulic cylinder has a larger stroke than the other), and the vehicle front end will typically be mounted to the side of the gantry with the shorter cylinder stroke to produce front-end-down pitch configurations, but the vehicle may also be mounted in the opposite orientation to permit testing in front-end-up pitch configurations.

The longerons and reaction structures are oriented in opposing directions, creating an asymmetric configuration that allows yaw configurations between 60 and 90 degrees to be achieved by rotating the entire gantry structure about the vertical axis as much as 30 degrees (for a 60 degree yaw test) (Figure 8), while still accommodating the full roadbed width.

During testing, the gantry's four vertical columns rest on 25.4 mm steel plates and the structure is anchored to the floor of test facility via two pairs (one on the leading side and one of the trailing side) of anchor clamps attached to ground mounting rails that clamp the longerons. The anchor clamps are adjustable in length and can be attached at any location along the length of the ground mounting rails permitting them to be used to anchor the gantry when it is used in any yaw configuration. To reposition the gantry between tests, the steel plates are removed, leaving the gantry resting on a set of four casters that allow the entire structure to be maneuvered into various positions.

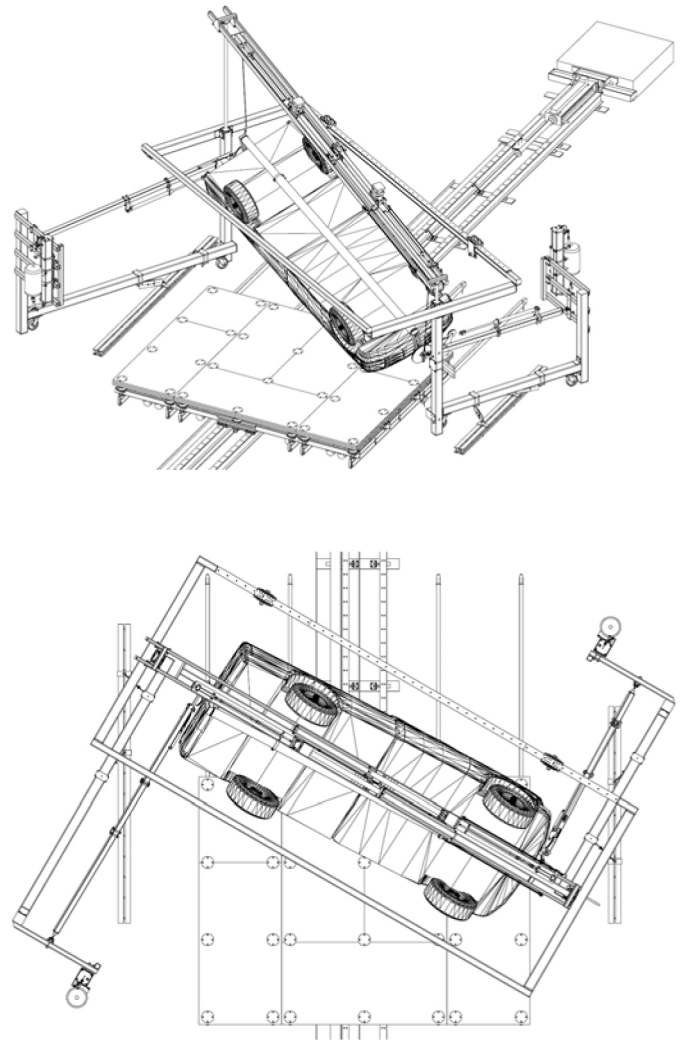


Figure 8. Isometric and top views of the DRoTS design, showing the 60 degree yaw configuration of the gantry.

Control Arms (Leading and Trailing)

The control arms are used to employ the main constraint on the vehicle during the test: they keep the roll axis in a vertical plane fixed at a specific location and orientation in the test facility. The leading and trailing control arms mount to the leading and trailing reaction structures with ball joints permitting free rotation about the three perpendicular axes. The other end of the arms attach to the vehicle support cradle

at the front and rear of the vehicle via a structure that permits free rotation of the vehicle relative to the control arms about the vehicle's roll axis and limited rotation about the axis mutually perpendicular to the vehicle's roll axis and the long axis of the control arms. This limited rotation allows for small changes in the distance between the ends of the control arms, which is required to allow the vehicle to freely pitch while remaining attached to the fixed-length control arms.

The reaction structures are designed to permit a wide range of vertical and lateral mounting locations for the control arms. The control arms are designed to be mounted such that they are perpendicular to the reaction structure (Figure 5) and parallel to the roadbed surface when the vehicle first contacts the roadbed during the test. Thus the mounting location of the control arms is a function of the vehicle shape (including length) and the pitch angle parameter.

The control arms are instrumented with load cells that capture the tensile/compressive loads on along the long axis of the arms, and encoders and potentiometers designed to capture the time history of the orientation of the arms.

The control arms also support the main roll drive cylinders and other associated components of the drive system.

Roll Drive/Brake System

The same system is used to provide the power to rotationally accelerate (drive) the vehicle before, and rotationally decelerate (brake) the vehicle after, the test. There are two individual systems, with pieces mounted to the control arm and reaction structure on each side of the gantry. Each system is a specialized combination air/hydraulic system consisting of two hydraulic cylinders, a pneumatic master cylinder, an ASME air tank, various servo cylinders, associated pneumatic/hydraulic plumbing and valve components, a drive cable and drive sheave (attached to the vehicle support cradle), a cable tensioner with two sheaves, a pneumatic cylinder and other components. The system combines pneumatic and hydraulic systems to allow for absorption of more energy during the braking phase than was extracted during the driving phase since the vehicle could increase its angular velocity as a result of interaction with the road. The system was designed to allow tests where either a single or both roll drive systems are used to accelerate the vehicle, which allows for greater ranges of parameter specifications (see Rotational Drive Performance).

During a test, air pressure stored in the tank is converted to hydraulic pressure, which causes the main roll propulsion cylinders to pull the drive cable attached to the cylinder piston. The other end of the drive cable is fixed to the main drive sheave (part of the vehicle support cradle) and tension in the cable causes the vehicle to rotationally accelerate. After interacting with the road surface, the drive cable is again wound up by the drive sheave, which pushes the hydraulic fluid in the opposite direction to remove rotational energy from the vehicle. All of the vehicle's rotational acceleration occurs over a roll rotation from 0 degrees to the roll angle at contact (i.e. numerous rotations are not necessary to achieve the test specifications).

The system is designed to be adjusted to permit independent specification of the angular rotation over which the roll drive system is activated, the roll angle at first roof-to-ground contact, and the roll velocity at first roof-to-ground contact by specifying the staging pressure and relative locations and orientations of the various components. The main pneumatic drive cylinder has a diameter of 168 mm, and the roll propulsion hydraulic cylinders on the control arms have a 30 inch stroke.

The storage tanks and pneumatic cylinders are able to operate over air pressure ranges from 100 to 1310 kPa. Again using the assumption of adiabatic expansion of the gas, performance envelopes in terms of roll rate vs. roll angle were calculated for three different vehicles (Figure 9): a small sedan (1998 Chevy Metro), a mid-sized SUV (1998 Ford Explorer) and a large SUV (1998 Ford Expedition). The moments of inertia for each of the three vehicles were determined from the literature (Heydinger et al. 1999). System efficiency was assumed to be 76%. The results of this analysis show that all three vehicles will be able to be tested at angular velocities between 111 and 264 deg/s for a 90 degree roll angle, and between 139 deg/s and 353 deg/s for a 180 degree roll. Smaller vehicles, in general, are able to be tested at higher roll rates for a given roll angle, and larger vehicles can be tested at lower roll rates for a given roll angle. Peak performance of the system for the large vehicle is a 264 deg/s after only 90 degrees of roll angle, and low-end performance is estimated to be 139 deg/s after 180 degrees of roll angle. High end predictions are made with both systems and the highest pressures, whereas the low-end predictions are made with a single roll system and the lowest pressure.

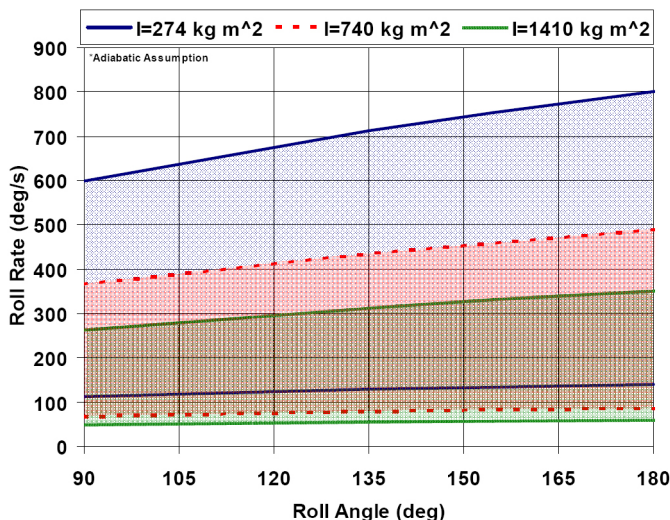


Figure 9. The performance envelopes for the DRoTS roll drive system in terms of roll rate vs. roll angle at test initiation for three different vehicles: 1998 Chevy Metro ($I=274 \text{ kg m}^2$), a 1998 Ford Explorer ($I=740 \text{ kg m}^2$), and a 1998 Ford Expedition ($I=1410 \text{ kg m}^2$). The roll drive system is capable of achieving any pair of parameters (roll rate, roll angle) within the performance envelope for each vehicle.

Cross Beam

The cross beam assembly connects the gantry column hydraulic piston rods via a fixed bridge and a sliding bridge. The cross beam serves to support the braking, triggered release, service decelerator and vehicle support hardware. The fixed bridge simply pivots, but the sliding bridge travels along the cross beam to accommodate varying cross beam angles as required for achieving various pitch angles.

Caliper Brake System

The caliper brake system consists of a pneumatic actuating cylinder, a caliper brake with shoes, a brake band, a cable return cylinder, a cable guide pulley and a range safety. There are two caliper brake systems, one for each side of the vehicle. Each vehicle support cable is routed upward from the vehicle support cradle, around the cable guide pulley and is attached to a brake band, which is, in turn, attached to the piston rod of the cable return cylinder. The caliper brake is oriented such that it will be able to clamp the brake band when the pneumatic actuating cylinder is activated. This clamping serves to restrict the car's vertical motion and is employed at the end of the vehicle's interaction with the road surface. In the event that the vehicle translates upward during the test, the cable return cylinder serves to keep the vehicle support cable in tension and aligned in the guide pulley.

The range safety consists of a pin, attached to the piston rod of a small switch-ready pneumatic cylinder inserted through an

oversized hole in the brake band. When the caliper brakes are released by the control system just prior to a test, the weight of the test article is transferred to the release mechanism (also attached to the brake band). If the brake bands move as a result of this transfer (which would indicate a problem with the release mechanism or another component), the cylinder will not be able to retract the pin from the hole, the vehicle will not be released and the test will be aborted.

All of the components of the caliper brake system are fastened to a support plate that is positioned according to the size of the test vehicle and clamped to the top of the cross beam.

Trigger and Release Mechanism

The trigger and release mechanism serves the purpose of releasing the vertical support of the test article at the time of the test. The trigger fuse is located approximately at the mid-span of the gantry cross beam and it consists of a pair of plates connected by a single 10-32 grade 8 socket head cap screw that is wired to serve as a fuse. When the trigger signal is received, current from a 12 V battery is passed through the screw, which melts the screw and releases the two plates simultaneously to release the vehicle's weight.

Service Decelerator

The test system is designed to permit a full-calibration test run where all of the test parameters are checked for accuracy without actually allowing the car to come into contact with the road structure. Since the release mechanism, range safety, and brake system need to be evaluated during a full-calibration test, a separate system must be used to arrest the vertical motion of the vehicle before it contacts the roadbed. The service decelerator system consists simply of angle brackets that hold pieces of steel tubing that, when installed prior to a full calibration test, interfere with pins sticking out of the brake bands when the vehicle is released. The interference causes the steel tubing to deform, which absorbs the energy from the vehicle and arrests its motion. Following the full-calibration test, the angle brackets are removed to ready the system for a real test.

Vehicle Support Cradle

The vehicle support cradle is fixed to the vehicle and is used to interface the vehicle with the control arms and roll drive/brake system. The cradle is made up of a set of telescoping tubes (13.3 cm and 15.2 cm diameters) that runs longitudinally underneath the vehicle at its lateral centerline and adjusts to accommodate various vehicle lengths. The ends of the tubes are attached to vertical supports which are in turn welded to the front and rear ends of the vehicle frame rails. The cradle interfaces with the control arms such that the vehicle/cradle center of gravity is aligned with the roll axis at the control arm interface in the front and rear. The main roll drive sheave (199 mm effective radius) is attached to the cradle at the top of the end posts, where it interfaces with the roll drive/brake

system. The cradle has provisions to make coarse and fine adjustments to the location of the vehicle center of rotation as necessary to align it with the structure's CG.

Lateral Control Link

The lateral control link consists of a single 304.8 mm aluminum rod connected to gantry's front support column and the interface of the trailing control arm and the vehicle support cradle via spherical (ball) joints at each end. This fixture is designed to prevent the vehicle/cradle from impacting the front/rear gantry support columns as a result of the longitudinal translation of the vehicle during the test. The multi-axis pivoting at both ends allows for the vehicle to freely translate vertically and pitch during interaction with the roadbed. The control link has adjustment in the vehicle's longitudinal direction to accommodate different sized vehicles and in the vertical direction to allow for the rod to be oriented perpendicular to the ground when the vehicle's roof first contacts the roadbed (making its mounting orientation a function of the test vehicle's geometry and the test conditions).

Control System

The roadbed propulsion, roll drive, roll braking, vehicle release, and vertical motion braking are all controlled by a programmable logic controller (PLC) system designed specifically for operation of this system. The control system permits independent variation of each of the test parameters while still ensuring precise timing of all actuations of the system.

DROTS VS. JRS

Since Safety Testing International (STI, Goleta, CA) has patented ([Friedman and Jordan 2008](#), [Friedman and Jordan 2010](#)) rollover test systems that utilize a moving road surface, the University of Virginia obtained a license from STI prior to development of the DRoTS. The DRoTS is similar to the JRS ([Friedman et al. 2003](#), [Jordan and Bish 2005](#), etc.) in terms of the constraints applied to the vehicle and the use of a vehicle roll axis that remains in a single plane. The DRoTS, however, incorporates operational and procedural differences compared to the JRS. The main difference is that, unlike the JRS, the DRoTS permits independent specification of test parameters, a feature which is required to perform parametric sensitivity analyses where a series of tests is performed to evaluate the effects of differences in only one test parameter (like roll rate or test velocity). More generally, the DRoTS has been designed to permit testing over a larger range of test parameters and vehicle sizes by incorporating a larger roadbed and a more powerful roll drive system, and the DRoTS utilizes a gantry/control arm configuration to improve stability of the structure, to permit measurement of the boundary condition loads and allow for easier loading of test vehicles. Lastly, the DRoTS incorporates some features necessary for testing of PMHS including a sealed road surface and a roll brake to arrest vehicle rotation after the tests.

ANALYSIS OF CONSTRAINTS

During a rollover test with the DRoTS, the vehicle's motion is constrained by the test system. Constraining the vehicle has the potential to restrict tests from simulating crash conditions that retain fidelity to real-world crashes, or to result in occupant dynamics that are not realistic. The following presents a discussion of some limitations of the test system (as designed) with regard to selection of test parameters, as well as a theoretical analysis of two potential issues that result from the physical constraints placed on the vehicle in the DRoTS. Lastly, issues resulting from the physical constraints applied to the vehicle are investigated computationally in the final section of the study.

FRICTIONAL EFFECTS

To ensure DRoTS tests accurately mimic the energy transfer between translational and rotational energy in real crash conditions, the time history of the vehicle's translational velocity during a rollover crash should be identical to the translational velocity time history of the roadbed in a DRoTS test designed to mimic the crash. However, in the DRoTS test, the roadbed is powered by a pneumatic sled system that continues to apply forces to the roadbed throughout its travel (including the roof-to-ground interaction phase) to oppose the frictional forces that exist between the roadbed and the sled propulsion and guidance systems. As a result, the time history of the vehicle's velocity in a particular rollover crash cannot, in general, be simulated exactly with the time history of the roadbed's velocity v^* in a DRoTS test designed to mimic the conditions of the rollover crash. While the velocity itself is not of particular concern in the DRoTS test, the forces transmitted to the vehicle by the road need to be accurately mimicked with the DRoTS to retain fidelity to rollover crash conditions.

In a rollover crash, if the vehicle's translational velocity v is equal to the tangential velocity of the part of the vehicle in contact with the ground (the product of the vehicle's angular velocity ω and the distance between its roll axis and the point in contact with the road r), then a rolling condition is established and there is no sliding at the interface between the vehicle and the road. In general, a rolling condition may not be present because the distance r changes with roll angle, and the presence of normal forces, when not directed toward the vehicle's roll axis, will effect the magnitude of ω . When v is greater than or less than ωr there is sliding at the interface between the vehicle and the ground that causes frictional forces at the interface that serve to transfer energy between the vehicle's translation and rotation. If we consider only how the frictional forces (and not the normal forces) affect the translational velocity and rotation in a rollover crash, when v is greater than ωr the frictional forces are directed in a way that could cause an increase in ω and a decrease v , and when v is less than ωr the frictional forces could cause a decrease of ω and an increase of v . The DRoTS permits both the rolling and sliding conditions that occur in rollover crashes and when the roadbed speed v^* is

greater than ωr , friction forces are directed in the same direction as the (rotating) vehicle exterior, which can cause an increase in ω , and opposite to the motion of the road, which could potentially result in a decrease in v^* (Figure 10). On the other hand, when v^* is less than ωr friction forces are directed opposite of the vehicle rotation, which could result in a decrease to ω , but in the same direction as the road motion, which could cause increased v^* (Figure 10).

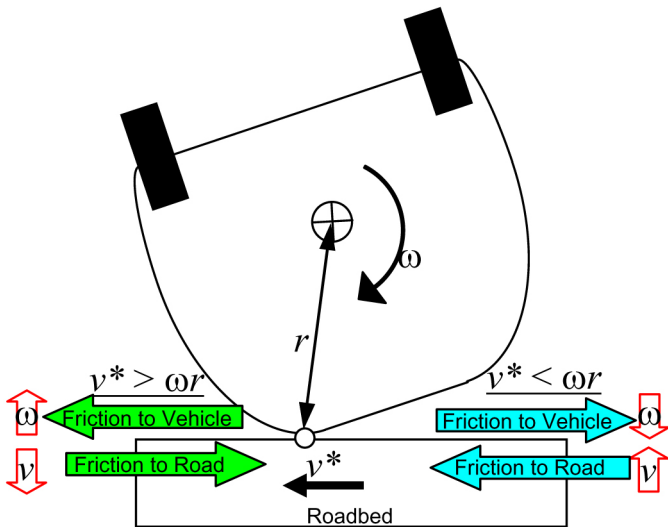


Figure 10. Schematic illustrating the effect of friction between the road surface and the rotating vehicle on the road surface's velocity v , and the vehicle's rotation ω .

However, if the sliding friction F_s between the road and the vehicle is modeled as Coulomb friction, it is equal to the product of the frictional coefficient μ and the normal force F_n

$$F_s = \mu F_n. \quad (2)$$

It can be seen that the magnitude of the friction force is not a function of the sliding velocity ($|v - \omega r|$) at the interface of the vehicle and the ground. This suggests that as long as v remains greater than, or less than, ωr throughout the entirety of the event, the frictional forces that result from a sliding condition will result vehicle kinematics and forces transmitted to the vehicle, that retain fidelity to rollover crash conditions. Since frictional forces are directed, in general, in a way that aims to force a sliding condition ($v \neq \omega r$) to become a rolling condition ($v = \omega r$), tests with the DRoTS should be run with sufficiently high ($v^* \gg \omega r$) or low ($v^* \ll \omega r$) road velocities to ensure that frictional forces do not force the sliding condition into a rolling condition during the roof-to-ground interaction.

If we look to the literature for guidance on which of the two sliding conditions are evaluated most (Figure 11), it can be seen that tests with the JRS are always performed with $v > \omega r$, whereas tests with the CRIS system are typically performed

with $v < \omega r$ initial conditions, although tests have been performed with both sliding conditions. Asay and Woolley (2009 and 2010) performed real highway rollover testing with both sedans and SUVs but used very high velocities to get vehicles to trip (15-29 m/s) with a steering robot and no power steering, so all of their tests occurred with $v \gg \omega r$.

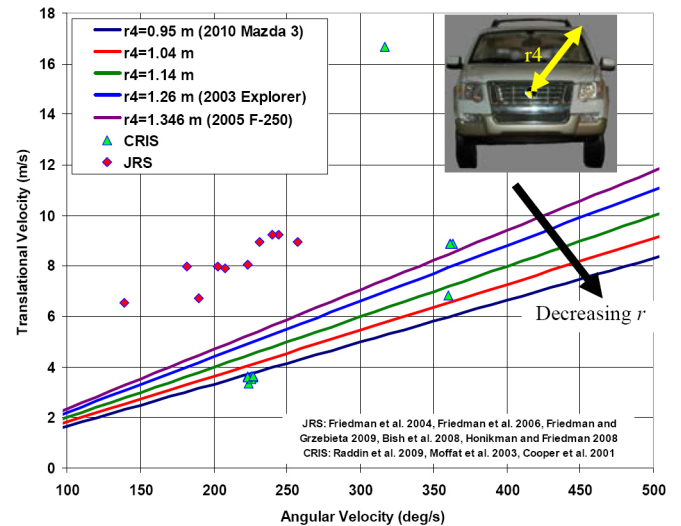


Figure 11. Translational velocity v vs. angular velocity ω with several lines of constant r , which represent the conditions in which a rolling condition would occur, and $r4$ (CG to roof rail) for three vehicles, showing test conditions from tests with the JRS and CRIS systems.

Since the two sliding conditions ($v > \omega r$ and $v < \omega r$) result in cases where frictional forces are applied to the vehicle in opposite directions, a research plan aimed at investigating parameter sensitivity in rollover crashes should evaluate both conditions since both conditions presumably occur in real rollover crashes. However, in the DRoTS, the road surface is only 3.66 m (12 ft) long, and in order to avoid edge effects, only 3.2 m (10.5 ft) of road can be used for roof-to-ground interactions. This constraint places a cap on the maximum road speed that could be used in a test: the period of time t_{int} equal to the change in roll angle during the test $\Delta\theta$ divided by the (assumed to be constant) angular velocity must remain less than the length of the useable road Δx divided by the road speed v^*

$$\frac{\Delta\theta}{\omega} = t_{int} \leq \frac{\Delta x}{v^*} \quad (2)$$

$$v^* \leq \Delta x \frac{\omega}{\Delta\theta} = 3.2 \frac{\omega}{\Delta\theta}. \quad (3)$$

For instance, a test at 200 deg/s that is to involve roof-to-roadbed interaction for 80 degrees of rotation (e.g. initial-final roll angle 140-220 deg), the road (useable length = 3.2 m)